WAVE PROPAGATION AND INVERSION IN SHALLOW WATER AND PORO-ELASTIC SEDIMENT

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LONG-TERM GOALS

To create codes accurately model wave propagation and scattering in shallow water, and to quantify effects of poroelastic, stratified sediment and elastic mode conversion. Also to relate these effects to sonar system behaviour and optimization-based inversion of sediment acoustic and elastic properties.

OBJECTIVES

Establish a Web page (*http://crimson.vis.utah.edu/~jwiskin*) consisting of several classes of Forward and Inversion codes for extensive simulation of wave propagation, scattering and inversion, in shallow water environments. This suite of codes is to be used ultimately to model sonar system behaviour in littoral regions. Develop k-space Integral Equation (KSIE) codes, finite difference time domain (FDTD) codes, and hybrid KSIE-FDTD 'pillbox' codes to model forward wave propagation, and optimization-based inversion codes to: (1) determine sea-floor parameters; and (2) locate and identify buried and semi-buried objects in sediment.

APPROACH

1. Establish a Web page from which other researchers are able to utilize the codes we develop and the computing power of the Origin class supercomputer available at Utah Center for High Performance Computing.
2. Extend the forward and inverse k-space integral equation (KSIE) solutions to include porosity and elastic parameters in 2 and 3D models by incorporation of porosity and other Biot parameters into the layered Green's function or dyadic.
3. Code a poro-elastic medium Green's function is to be used in conjunction with the pill-box code, which is presently in process of extension from acoustic to the elastic and poroelastic cases.
4. The 3D problems will be parallelized to run on the U. Utah's SGI power challenge (a 16 processor shared memory computer), the workstation cluster (a 16 node heterogeneous cluster of workstations), and the IBM SP2 (a 64-node multiprocessor) and

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the Origin2000/Onyx2 InfiniteReality system (a 60 processor, scalable, distributed shared memory architecture that provides a follow on to the SGI PowerChallenge class of symmetric multiprocessing systems. The Onyx2 InfiniteReality Graphics Pipes are high performance visualization graphics engines).

5. Code the acoustic finite difference time domain (FDTD) equation with PML (Perfectly Matched Layer) boundary conditions.

6. Incorporate dispersion into the above FDTD-PML code.

7. Code a contour-integral approach to calculation of the wavenumber integral required for the calculation of the Green's function in a layered acoustic, elastic, or poro-elastic medium to speed up the calculation.

8. Incorporate the FDTD and KSIE approaches into a unified "pill-box" code -- utilizing the advantages of each model.

9. Develop Parabolic k-space Code. Our code appears to differ from the codes available presently (eg. M. D. Collins) in the approximation of the propagator. Our approach yields a more accurate approximation with only a slight increase in computational complexity. [2]

10. Develop pseudo-analytic (expansion in basis functions) solutions to the problem of an elastic scatterer in a stratified elastic medium and compare with data collected at the experimental facility of TechniScan, Inc., a biotechnology spin-off company from the U. of Utah.

11. Generalize the PML boundary conditions for FDTD to the elastic case from the acoustic case and code. Test this and other codes and create a Web-based interface using Java or similar language to the codes so experimentalists can utilize the codes.

WORK COMPLETED

We have established a Web page for the Center for Inverse Problems Imaging and Tomography, and are adding Technical reports and Codes to it. We have parallelized the acoustic integral equation inversion code using PVM and the acoustic FDTD codes using MPI. The FDTD with causal dispersion (ie. satisfies Kramers-Kronig) and PML has been written, tested and documented in 2 and 3 dimensions [1,4]. We also have faster FDTD code with dispersion, but without the PML boundary conditions [3]. The Advanced Parabolic Method has been written and tested in 2 and 3 dimensions. [2] for acoustic field propagation. The contour integral code has been completed and is undergoing testing for the acoustic stratified Green's function. We have adapted code generated by J. Schuster in Geophysics for the FDTD model of Biot media. Elastic FDTD code with pseudo-PML boundary conditions have been derived in theory, and coded. The PML helped but boundary reflections were greater than the acoustic PML case. Further work needs to be carried out. The acoustic 2D pill-box code has been completed and is undergoing testing now. The pillbox is designed to enclose the target. See Fig. 1. The source(s) and receiver(s) are some finite distance away. The pill-box can be partly in water and partly in sediment, and the target can be also partially or totally buried in sediment. We used time domain codes to effectively generate the Green's function in this case, since the porous media elastic layered Green's function is not yet coded. See Fig. 2

RESULTS

We have tested our k-space IE (KSIE) codes against our time domain FDTD with PML and dispersion, and obtained excellent agreement. We have found that IBM Data-Explorer can be used to process data collected from our simulation codes to produce insightful snapshots of the scattering from semi-buried and buried objects.
Initially we were planning to use the KSIE codes to model sonar performance. We discovered that the high contrast objects yielded slow convergence of an otherwise powerful algorithm. This led to development of the FDTD/KSIE hybrid "pill-box" wherein the FDTD codes are used to model interaction of the wavefield with the target, and Green's theorem is used to propagate the scattered field back to remote receivers.
We have used collected data from a brass sphere in water to compare our series solution with experimental data collected by TechniScan, Inc. in their water tanks. Agreement was excellent. We have also reconstructed augur cylinders from lab data with inverse scattering.

IMPACT/APPLICATIONS

The FDTD with dispersion, the KSIE, and the hybrid "pillbox" will be made available on the Internet so that it can be accessed and used by other researchers. This pillbox code will enable the forward modeling of much larger regions than has been possible in the past, while still including *all* orders of scattering between a semi-buried object and the sediment interface. The presence of dispersive material in the time domain is difficult to model in a computationally efficient manner. We have employed two independently derived methods to include dispersion. Our algorithms have implications that go far beyond acoustic inversions and modelling, and have repercussions in environmental imaging [5], acoustic imaging [1,4,5,6,7] and early breast cancer diagnosis.

TRANSITIONS

We have combined the FDTD and k-space Integral Equation (KSIE) approaches into one hybrid "pill-box" code. This code is now written for the 2D acoustic case. It must be extended to the 3D case and parallelized. The FDTD and KSIE parts must be independently parallelized and an interface made available on the Internet through the Center for Inverse Problems, Imaging and Tomography (CIPIT) Web site.
The newly created Center for High Performance computing and the Origin2000/Onyx2 InfiniteReality system make the U. of Utah one of 5 or 6 such sites nationwide with such computational and visualization capabilities. We will work with the Center to utilize the visualization/computational capabilities by adapting our code to run efficiently on their machines. Thus enabling larger sized models to be run than otherwise possible.

RELATED PROJECTS

There are a large number of related projects dealing with the imaging of sediment characteristics and objects buried within sediments which impact our work and vice versa.

We are presently developing codes that could be used by these groups over the Web, and our codes should be tested using the results of other groups' research. For example:
1 Scattering Dynamics of proud and buried underwater objects -- R. Lim, Coastal Systems Station presently has a b version of our Dispersive FDTD/PML code, 2 Dilip Ghosh-Roy/Louise Couchman at ONR, 3 Norman Bleistein at the Center for Wave Phenomena, 4 Univ. of Victoria/MIT/WHOI experiments and theoretical studies, 5 Geoacoustic Benchmark Workshop, 6 Three-Dimensional Acoustics in-situ imaging of sediments at APL, U. of Washington, 7 Nick Chotiros, Applied Research Labs, U. of Texas, Austin. We also collaborate with M. Zhdanov, J. Schuster in Geophysics at the U. of Utah, and Frank Natterer in Germany on inverse problems.

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Test simulation for the "pill-box" FDTD algorithm

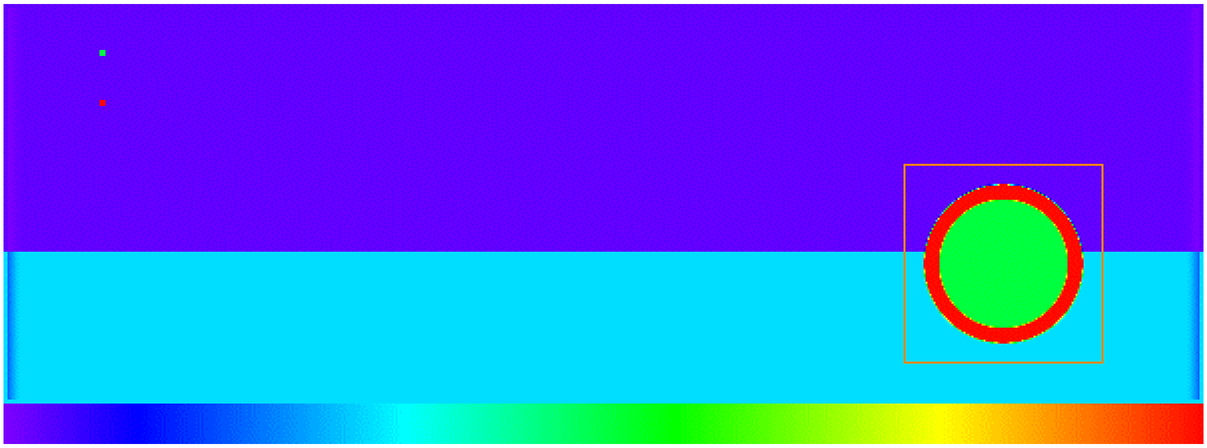

Figure 1. 600 × 200 pixel FDTD model. The color represents speed of sound from 1500 m/s (dark blue) to 4000 m/s. (red) Also shown are the transmitter point (red dot), the receiver point (green dot), and the 100 × 100 pixel pill-box (orange square). The sediment speed of sound is 2500 m/s, the water speed of sound is 1500 m/s, the cylinder outer shell speed of sound is 4000 m/s, and the material inside the shell has a speed of sound of 3000 m/s. The image is 3.75 × 1.25 m. The cylinder inner diameter is 0.4 m and the outer diameter is 0.5 m.

Transmitter bandwidth = 0 to 30 KHz Blackmann window.

The pixels are 1/8 of a wavelength in water at 30 KHz = 6.25 mm

The FDTD algorithm is fourth order in space and second order in time and uses a 9 pixel thick PML boundary condition.

All materials in the model are lossless with a mass density equal to that of water.

The full sized (600 × 200) FDTD for 7000 time steps required 21 min. on an HP 750 workstation (15 to 20 MFOP's).

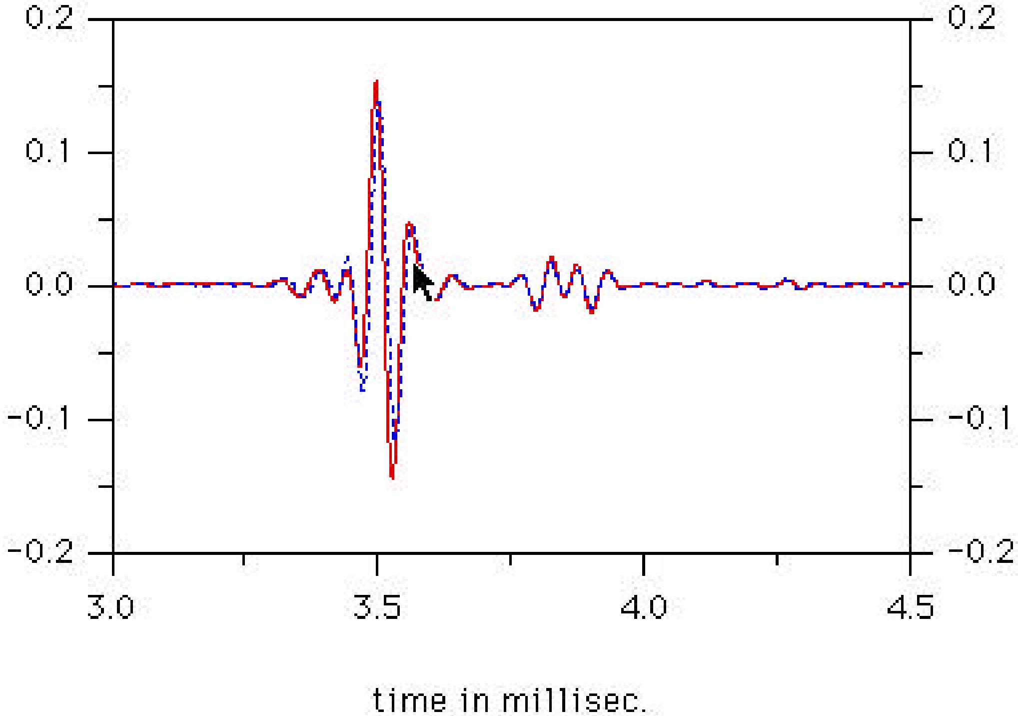

Figure 4 compares the time waveform at the receiver point computed by the 7000 time step, 600 by 200 FDTD run (solid-red) and the 2400 time step, 122 by 122 pill-box FDTD run (dashed-blue).